Astronomy Cast Episode 18:
Black Holes Big and Small

Fraser Cain: We're finally ready to deal with the topic you've all been waiting for: Schwarzschild Swirlers, Chandrasekhar Crushers, Old Matter Manglers, Singularities, Black Holes. Objects with gravity so powerful that nothing – not even light – can escape. All right Pamela, start nice and easy! What is a black hole?

Dr Pamela Gay: A black hole is basically an object that has shrunk down so small with all of its mass, that it's actually possible to get close enough to all of that mass that you would have to go faster than the speed of light to get away from it. Our planet Earth is like a "people-hole" : no matter how hard I jump, I can't jump off the surface of the planet. Well a black hole is an object that is so dense that its gravity so strong that light can't get away from it.

Fraser: It's a great analogy: the more massive an object gets, the stronger something has to be to escape, or the faster-moving something has to be to escape. With black holes it's the speed of light, and as nothing moves faster than light, that's that.

Pamela: Yes, you're stuck! Now the catch is that any object, if you make it small enough, can become a black hole. The planet Earth would be a black hole if you could squish all its mass down to just a couple of millimetres across. It wouldn't be a very impressive black hole, but if you got close enough you would be trapped on the Earth. But because the mass is spread out over such a large area, the gravitational effects aren't that strong at the surface.

Fraser: So where did we come up with the idea of black holes?

Pamela: As far back as the 1784, the geologist John Michell started thinking "Well, we have this idea of Newtonian gravity, and we know about escape velocities, so let's figure out just how big something has to be so that you have to go at the speed of light in order to escape."

His calculation said that you had to have something about 500 times the radius of the Sun and the same density as the Sun at its surface to not be able to escape going at the speed of light. Physics has been upgraded since 1784 and we know that, with relativity, it's a little more complicated. But the idea has been around for a long time.

Fraser: So what's the more modern thinking about what's going on inside a black hole?

Pamela: There are actually two different types of black hole; there are those that are 4-15 times the size of the Sun, then there are those that are thousands of times the size of the Sun, while a stellar-mass black hole is a star that at some point just stopped producing the energy that supported the outer layers of the star. When those outer layers collapsed in, the particles could not support the weight of all of the material pressing down on them.

If you have an object of more than 1.4 Solar masses, when the mass collapses the protons and electrons smash together and all of them fuse into neutrons; there is energy and bits escaping, but you end up with a neutron star.

If an object a little more than 3 solar masses collapses, it just keeps going, as neutrons (nor anything we can really understand) are not strong enough to hold the weight, so the star keeps collapsing. According to the math that we are working with today, you end up forming a singularity out of the material. But within the Schwarzschild radius…

Fraser: Sorry, what's a singularity?

Pamela: Basically, it's an infinitely dense point. You take all the matter and crush it down so it has basically no radius.

Fraser: So the pull of gravity is so strong that the matter is mashing the particles down to nothing?

Pamela: They basically reduce down to energy. Some people say it's a "quark soup". We don't fully understand the particle physics in this dense an environment. Our theories sort of stop once you get inside a black hole and there are some really powerful minds working on this, Stephen hawking, for instance.

Fraser: So what does Stephen Hawking think?

Pamela: Stephen Hawking is working on a theory of quantum gravity that is beyond the ability of anybody but the most intelligent experts in that field to understand, but there are indications that some really neat things are going on. For instance, there had been a long term bet between Hawking, Kip Thorn, and John Preskill about whether black holes consume information. One of the basic ideas of physics is that no information is ever lost and that, at a certain level, all of the information can somehow be gotten back.

But if stuff falls into a black hole never to come about again, that information is clearly getting absorbed into the black hole and lost forever. Or at least, that's what people thought, but physics says information is never lost, so for a while there was a debate in which Thorn and Hawking said "Information is lost, black holes are unique", but Preskill said "No, information cannot be lost, that's the rules of physics".

Back in 2004, Hawking announced that maybe there were quantum perturbations at the event horizon of the black hole, and that information was able to come out through the stuff called "Hawking radiation", or maybe there is information left behind if a black hole completely evaporates. This opens up fascinating things to talk about and he decided that information never is lost, so he paid Preskill in the form of a baseball encyclopaedia, with information he could always look up, as information is not lost.

Kip Thorn is still not convinced and has not yet paid his half of the bet, but these guys are doing complicated work to deal all the weird physics going on at the event horizon of a black hole.

Fraser: So, we have a star with 4-15 times the mass of the Sun, the fusion stops and it compresses down to possibly an infinitely small amount of space which we call a singularity, but it still maintains its mass. So what would we see if we were in the region of a black hole?

Pamela: If we were the poor schmuck who fell into the black hole, we would see ourselves falling in and all sorts of bad things would happen to us; we would get stretched out, our body would be torn apart by the tidal forces of gravity being not as hard on our head as on our feet (if we were falling feet first) and this would all happen fairly rapidly, at least in our perspective.

But if we have a buddy a little further away, in a safe place not falling into the black hole, they would see us falling towards the black hole and continually slow down as we go, and get increasingly more red because the light coming from us would get red-shifted by the powerful gravity of the black hole. Eventually we would not be seen to fall into the black hole but - over an infinite amount of time – we would be seen to fade away.

Fraser: So the gravity of the black hole is stretching out the wavelengths of our light as it's trying to escape the pull of the black hole.

Pamela: Yes, the light gets gravitationally red shifted because the wavelengths spread out.

Fraser: So you don't actually disappear so much as fade away. Shouldn't we be able to see black holes as very bright objects because they are surrounded by all the matter they have consumed?

Pamela: Actually, what is even brighter around black holes is their accretion disk. If something gets too close to a black hole, the material falling in will spiral around and form a disk of material. You get similar structures around white dwarf stars and neutron stars, as material falling into more or less any really compact object will form an accretion disk, which is so dense that there can be nuclear reactions going on within the disk. So, in some cases, this disk behaves almost like a star.

Fraser: So it's as if the material is choking the black hole, which cannot eat it fast enough, so its backing up and the environment of this material becomes almost stellar in nature. It's like when we talked about the first few moments of the Big Bang, when the whole universe was like the inside of a star.

Pamela: The conservation of angular momentum chokes the rate at which the material can fall into the black hole. It can't just fall straight in unless it has a magically perfect trajectory (which never really happens). So the material gets choked up by the conservation of angular momentum and ends up creating this accretion disk which has amazing reactions going on within it, and that's actually how we identify where we think black holes are located.

Fraser: That was going to be my next question: if black holes are black, how can we find them?

Pamela: We look for all the signatures of things can only happen near a black hole: rapidly rotating, highly dense accretion disks, and we can use the rate at which they are rotating to judge how massive the object at their centre has to be. So if you have a rapidly rotating accretion disk that indicates the mass within it is greater than about three solar masses, you have a pretty good clue that it probably has a black hole in the centre.

Fraser: Will it have a special signature that we can see in certain kinds of telescopes?

Pamela: These environments are generally so dense that the material gets so heated that we see x-ray emissions. So we can look for x-ray emissions as a signature of black holes.

Fraser: What about their mass? Does that have an effect on their local environment?

Pamela: That's where the rotation rates come in. Things that are near a high mass object will orbit it much faster than those orbiting a low mass object at the same distance, so we look at something and see that the accretion disk is going super fast (mathematics, mathematics...!) and we can calculate the mass at the centre of the accretion disk, and using that mass we can figure out whether it's a neutron star, a black hole or a white dwarf.

We can use Doppler shifts and measures of spectra to get at the rates of rotation (in the same way that a police officer can get the rate of how fast your car is going) and use that to identify where black holes are located.

Fraser: Earlier we talked about two sizes of black holes: stellar mass and those which are much larger. So what are those?

Pamela: There are also things called "supermassive black holes"that are somewhere between hundreds of thousands and tens of billions times bigger than our Sun.

Fraser: What percentage of the mass of a galaxy is that? There must be a big chunk of a galaxy just in that black hole.

Pamela: It's a huge amount. These things form the core of galaxies, and the mass of a supermassive black hole in the centre of a galaxy is actually related to the size of the halo of a galaxy and how fast the stars within the galaxy are moving. These are basically the angry monster sitting at the core of every galaxy just waiting to feed on in-falling material.

Fraser: So there's one at the heart of every galaxy?

Pamela: As far as we can tell, every galaxy has one in proportion to its size, and in fact, these things answer a lot of questions in astronomy; quasars, for instance, are most likely black holes that are in the process of feeding on mass gas and dust that are falling into their centre.

Fraser: So that the backing up of material around the black hole?

Pamela: As the material falls in it gets lit up; sometimes jets form, and it's the jets that we can see in different types of objects. Active galactic nuclei, with amazing jets shooting out the ends, are black holes with jets which are just a side effect of the environment around the black hole.

Fraser: How come you get those jets?

Pamela: It's this neat combination of what happens when you combine magnetic fields and in-falling material. Sometimes the material falls in along the 'equator' of the black hole and, as it falls, it gets twisted into the magnetic field and shot out the poles of the rotating black hole.

Fraser: What impact does one of these supermassive black holes have on its galaxy?

Pamela: The impact comes in terms of ending up with a huge central core shooting off huge amounts of radiation, but it's localised to the core and the jets that are coming out of the poles. So you can still end up with star formation going on, and probably planet formation, just further from the centre. In fact our own Milky Way galaxy probably contained an active, consuming quasar black hole in its centre. We have the black hole today, it's just not angrily feeding on dust and gas that's falling into it.

Fraser: So we have a supermassive black hole at the middle of the Milky Way.

Pamela: And it's not feeding on any gas and dust because there's none falling into it today.

Fraser: So how was that discovered?

Pamela: Simply by looking at the stars. Andrea Ghez, Professor of Astronomy at the University of California, Los Angeles, took high speed images of the centre of the galaxy so that she could align and stack the images in such a way that she could look through the atmospheric crud, and the dust and gas between here and there, and actually see the stars that are very close to the centre.

Over the course of ten years, she could watch these stars move; they would go half way round the centre of the galaxy while she was watching. Using the observed motions of these stars, she was able to calculate the mass of the object they had to be orbiting. Mathematically, it had to be a black hole (or some other object that no one has yet conceived of that is impossibly large and dense) that's just sitting in the centre.

Fraser: There was a PBS special about three months ago where they showed the graphics that she built up. It was amazing to see the stars, several times the size of our Sun coming in then doing almost a quick turn around a point in space, then zooming back out, like comets orbiting the Sun, with bizarre orbits. I guess nothing could provide enough gravity but a supermassive black hole.

Pamela: There's no way to pack enough normal stars into such a small area so as to get this gravitational effect. It's one of the most breathtaking pieces of science to look at because you can see stars dramatically move like you would expect planets or comets - things local to our own solar system - to move.

Fraser: I'm sure people are going to want to know whether we are at any danger from these supermassive black holes at the heart of our galaxy.

Pamela: Absolutely none. We are safe!

Fraser: Not even a trillion years from now?

Pamela: Well, I really wouldn't want to talk about a trillion years from now, because bad things are going to happen between now and then, like we are going to collide with the Andromeda galaxy, and then a lot of weird stuff is going to happen, because our supermassive black hole and Andromeda's supermassive black hole will come together and orbit one another and perhaps even merge over time.

There are several merging galaxies where you can see these supermassive black holes near one another, with all the fabulous fireworks going off; they trigger star formation, they have jets and they're accreting matter. It's fabulous fireworks! When we collide with another galaxy, I really can't speak to our safety, but until that happens, I'm fairly certain we're safe.

Fraser: Is our Sun going to turn into a black hole?

Pamela: No. Our Sun is just not fat enough. It's just hanging out maintaining it's weight quite nicely. It occasionally loses weight through mass loss, and the older it gets, the more mass it will lose through solar winds, and unless it finds some way (which physics cannot predict) to gain three times its current mass, we are totally safe.

Fraser: So what would happen if a black hole came through the solar system?

Pamela: We would die! Phil Plait from Bad Astronomy does a brilliant talk called "Seven Ways a Black Hole Can Kill You!" asking questions like "What would happen if a black hole *did* wander through the planet Earth, or through the Sun?" But we don't know of any black holes that are going to do this, so we should be safe.

Fraser: Except they're black and you can't see them coming!

Pamela: Right, but they grab dust and gas as they go through it and light off fireworks as they go, so – as far as we know – we are totally safe from randomly wandering, isolated black holes.

Fraser: That's good! Will black holes last forever; is the end of the universe going to be when every piece of matter has found its way into a black hole?

Pamela: That's one of the neat things; black holes that are small enough can actually evaporate, just like water will evaporate from a glass after a time. But this is only true for small ones.

Fraser: But how does it evaporate?

Pamela: Throughout the universe, virtual particles are bubbling in and out of existence, so you can get an electron and a positron that spontaneously form and almost instantaneously come together and self annihilate. If these things form on the event horizon of a black hole, one may be on the outside of a black hole and be able to escape, while the other gets sucked in.

So the two never meet and annihilate one another, and you end up with particles bubbling up at the event horizon which escape the black hole and allow it to evaporate. This is called "Hawking Radiation". If you have a big enough black hole, the amount of particles and energy that it absorbs just from the cosmic microwave background radiation is probably just enough to counteract the effects of evaporation, but small black holes can actually evaporate away.

Fraser: And then bigger black holes will eat those particles and everything will end up in the really big black holes.

Pamela: Exactly!

Fraser: OK!

Pamela: But there can still be things like white dwarfs, neutron stars and even rogue planets which never get close enough to a black hole to fall in. So it's not that *everything* is going to be a black hole, but there will be a lot of them!

Fraser: Another grim future from Pamela! Thanks, that was great. Talk to you next week Pamela.

Pamela: Talk to you later.

This transcript is not an exact match to the audio file. It has been edited for clarity.

Transcription and editing by Colin Humphries